IN-SITU MEASUREMENT OF GROUND STIFFNESS USING SUPER FALLING WEIGHT DEFLECTOMETER TEST METHOD

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ABSTRACT

In the design and construction of the road and structure foundations, in order to effectively prevent the residual settlement and the insufficiency of bearing capacity, reliable in-situ test methods which enable the measurement at high accuracy and repeatability are necessary. Plate loading test is the most commonly used method for in-situ measurement of ground stiffness. However, this method is considered to be time-consuming and costly for multi-point measurement.

Therefore, based on the simple principle of Falling Weight Deflectometer (FWD) method for pavement investigation, this **Super Falling Weight Deflectometer (SFWD)** method for measuring ground stiffness at high accuracy thanks to escalating rapid loading and accumulative displacement measurement was developed and applied at actual construction site. The ground stiffness measured by this method was found to be equivalent to that measured with plate loading test. In addition, with the advantage of simple and quick measurement using this method, it is now possible to early evaluate the ground stiffness to provide reliable information for consideration of construction method and process.

This paper describes the outline of this test method and the result of the actual application at some construction sites.

1. INTRODUCTION

For evaluating the stiffness of ground, there are two approaches as can be seen in Table 1: One is the direct calculation of ground stiffness based on load and displacement (Plate Loading Test, In-Situ CBR Test, FWD, Light Weight Deflectometer, SFWD), the other is the indirect evaluation using acceleration index (Automatic Compression Testing Machine, Intelligent Compaction).

The ground stiffness evaluation using loading plate is applicable for grounds of which maximum size of soil particles is less than one third, and measured depth is less than twice of plate diameter

Though plate loading test is the most commonly used method, it requires a large reaction base. Furthermore, it is quite labor and time-consuming, taking several hours for one measurement. On the other hand, though the indirect method using acceleration index value is quite simple, its range of applicable ground as well as the measuring accuracy remains great challenges.

FWD and Light Weight Deflectometer are common methods in which a weight is dropped repeatedly 6 times from the same height and the ground stiffness is evaluated based on the measured results. The first drop is preparatory loading for eliminating the bedding error. It also creates a loading history in the tested ground. Therefore, the ground stiffness obtained after first drop is the one under repeat loading, and is, therefore, different from the ground stiffness in term of K value obtained under monotonous loading of conventional plate loading test.

SFWD system (Figure 1) utilizes the principle of FWD but the way of applying load is quite different. In this system, the load is applied in multi stages with escalating rapid loading while the accumulative displacement is measured. The ground stiffness is defined as the envelope gradient of load-displacement curves.

As a result, it is quite simple to obtain equivalent K-value as in case of using plate loading test, and in-situ evaluation of ground stiffness is relatively easy with this method.

Table 1　In-Situ Measurement Methods for Ground Stiffness

		Measured item	displacement accuracy	plate size (mm)	pre-loading	Evaluation of K-value	Correlation to K-value of plate loading test
Direct	Plate Loading Test	displacement & load	high	ϕ300～ϕ750	no	——	——
	In-Situ CBR Test	displacement & load	high	ϕ50	no	conversion	low in gravelly soil
	FWD	displacement & load	high	ϕ300～ϕ450	applied	cyclic loading	medium
	Light Weight Deflectomter	acceleration & load	medium	ϕ100～ϕ300	applied	cyclic loading	slightly low
	SFWD	displacement & load	high	ϕ300～ϕ450	no	equivalent to plate loading test	high
Indirect	ACTM*1)	acceleration	——	ϕ50	applied	conversion	extremely low
	Intelligent Compaction	acceleration	——	roller width	no	conversion	low

*1) Automatic Compression Testing Machine

Figure 1　Measurement at a Construction Site using SFWD

2.　OUTLINES OF SFWD SYSTEM AND DATA PROCESSING METHOD

In SFWD measurement, a weight of 200kg is repeatedly dropped onto ground from gradually increased heights. It means that load with increasing intensity is applied continuously on ground and the ground stiffness is evaluated from the measured accumulative displacement. The maximum load corresponding to the maximum dropping height of 300mm is as large as 90kN, which means that a great impact on the ground is possible.

As can be seen in Figure 2, this system is an integration of load and displacement measuring functions. Devices for loading, displacement measurement, GPS signal, etc are controlled by a computer which is also used for analyzing measured results and evaluating ground stiffness. Table 2 shows the parameters of this system.

It is a totally automatic system which enables a fast, highly accurate and simple method for evaluation of ground stiffness. Therefore, the measurement of ground stiffness is largely optimized, the construction is more effective, and the quality assurance is very much simpler than before. Example of ground stiffness evaluation based on measured results is shown in Figure 3.

Figure 4 shows the load and displacement results in which the weight was dropped from different heights of 60, 175 and 300mm.As can be seen in this figure, the time duration from the start to the pick of loading is as small as 0.01 second. It means a great impacting load has been applied.

Figure 5 is a computer display showing the “Result Analysis” dialog of SFWD system. In the same display, one can see such information as load, displacement, load-displacement relation, and load–cyclic deformation modulus relation on the real time basis. Besides, the ground stiffness is also evaluated and shown at the same time.

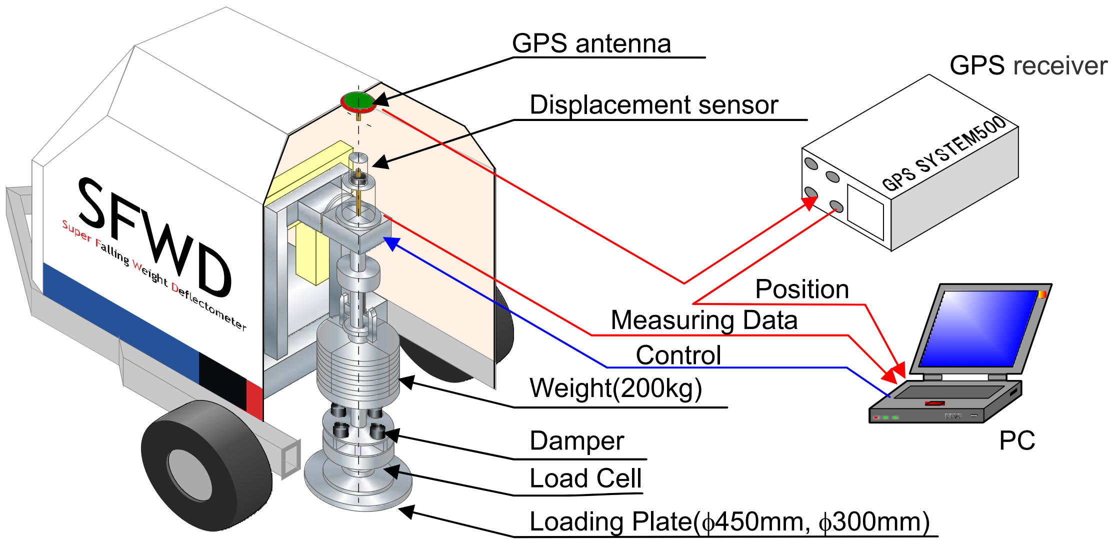


Figure 2　Super Falling Weight Deflectometer(SFWD)

Table 2　SFWD Specification

Weight	200kg
Maximum Falling Height	300mm
Maximum Rapid Loading	90kN
Diameter of Plate	ϕ 450、ϕ300
Loading Sensor	load cell
Displacement Sensor	GY & LVDT
Range of Displacement	0~30mm

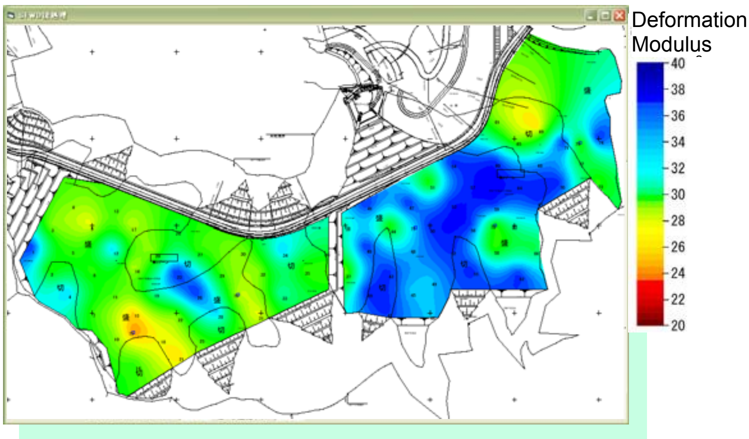


Figure 3　Sample of a Distribution Map of Ground Stiffness Measured bv SFWD

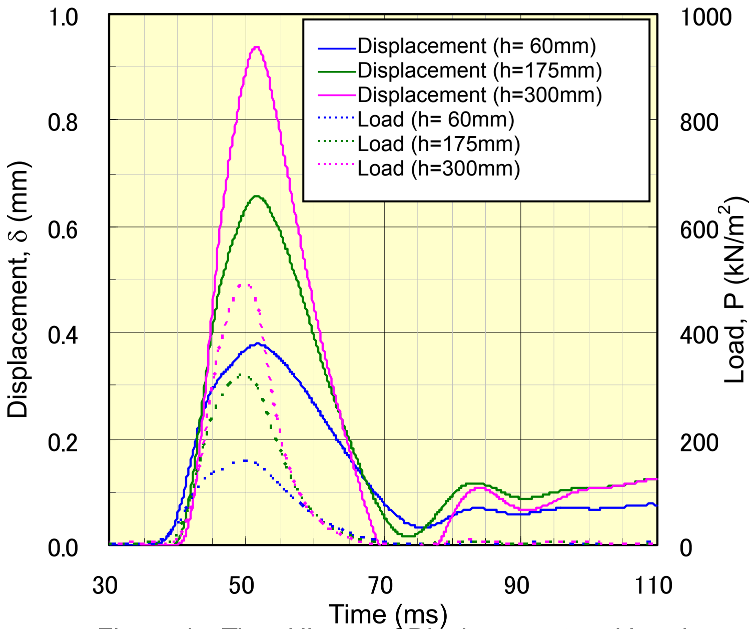


Figure 4　Time History of Displacement and Load

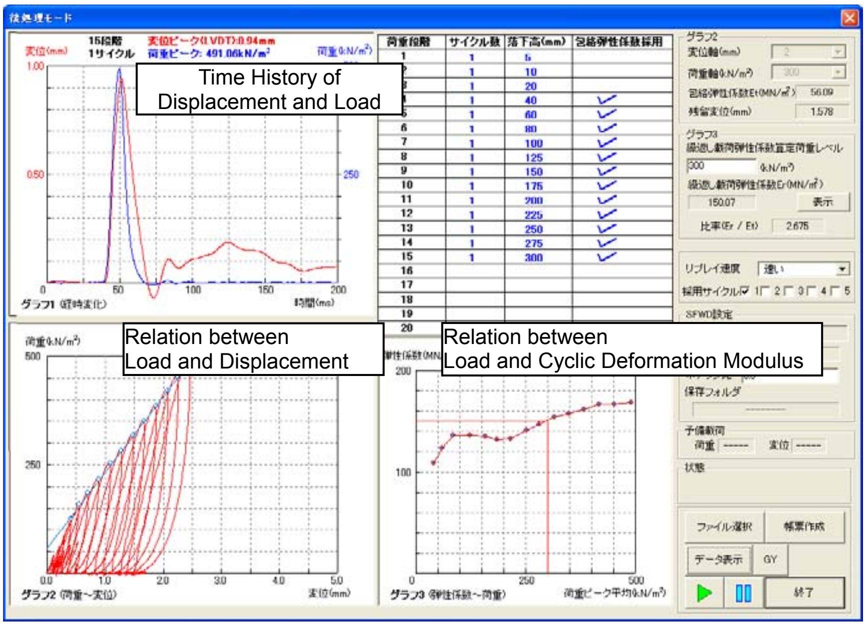


Figure 5 Sample of Output Obtained by SFWD Measurement

Figure 6 shows the concept of [multi-stage rapid loading - accumulative displacement] method

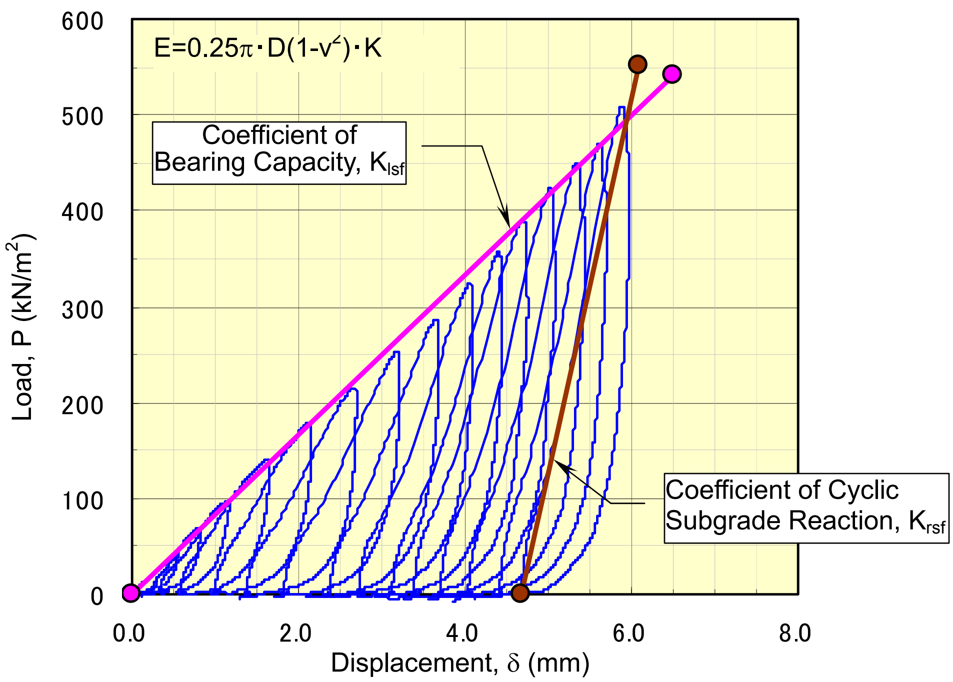


Figure 6 Multi-Stage Rapid Loading-Accumulative Displacement Method used in SFWD

used in SFWD system. As seen in this figure, the coefficient of bearing capacity, K_{lsf}, is defined as the envelope gradient of all load and displacement peak values of each loading stage, and the coefficient of cyclic subgrade reaction, K_{rsf}, is defined as the gradient of each load and displacement start and peak values of each loading stage.

The deformation modulus E_{lsf} of SFWD system is calculated using the following formula in which the coefficient of bearing capacity, K_{lsf}, under plate loading condition is a variable.

$$E_{lsf}=0.25\pi\ D\ (1-\nu^2)\ K_{lsf} \qquad (1)$$

Here, ν: Poison's ratio (0.3 for sand or gravel, 0.4 for clay)

D: Diameter of loading plate

3. LABORATORY TEST FOR VERIFICATION OF MEASURING ACCURACY

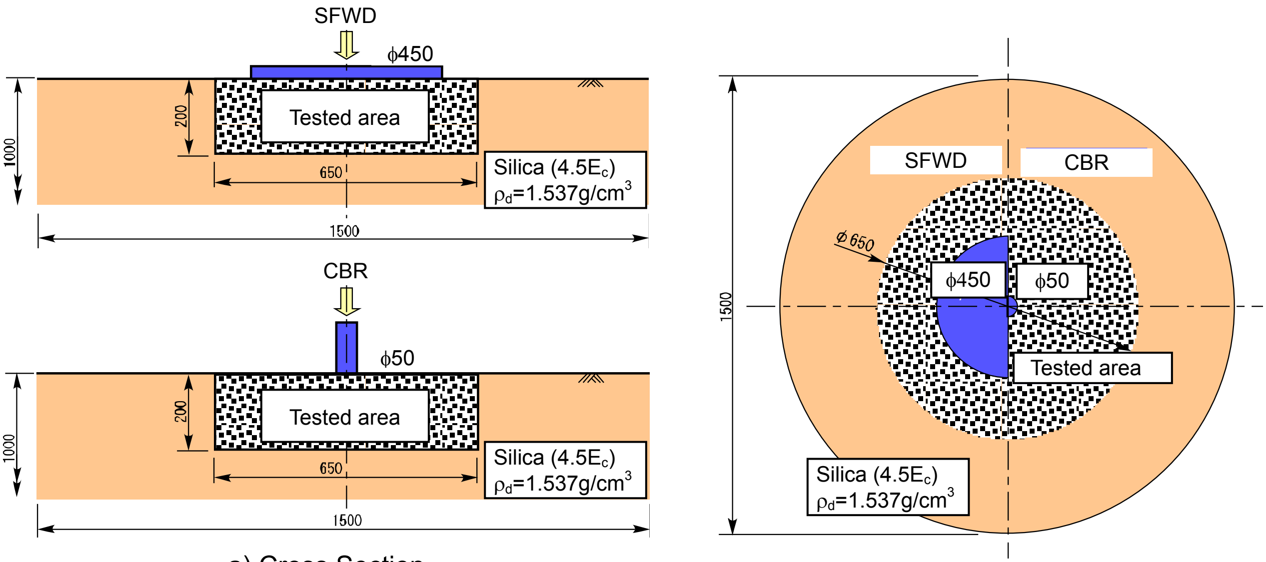
In order to verify the accuracy of SFWD system, laboratory plate loading test, in-situ CBR test and SFWD measurement were carried (Figure 7).

Figure 7. Laboratory SFWD Test

3.1 TEST CONDITIONS

Tested ground with dry density, ρ_d, of 1.537g/cm^3 was created by compacting silica into a large cylinder with a compacting energy of 4.5E_c (E_c : compactive effort ≈ 550kJ/m^3) and it has diameter of 650mm and thickness of 200mm.

For comparison with plate loading test, tested soil was modified by replacing silica with crusher-run (D_{max} = 40mm) and compacting with energy of 0.15E_c. On the other hand, for comparison with in-situ CBR test, the compaction energy was varied from 0.5E_c to 4.5E_c and part of silica in tested soil was replaced by crusher-run (D_{max} = 40mm).



a) Cross Section

b) Top View

Figure 8 Laboratory SFWD Test Configuration

3.2 COMPARISON WITH PLATE LOADING TEST

Figure 9 shows the load-displacement relation obtained in SFWD measurement and plate loading test. This figure also shows a good agreement of deformation modulus obtained by SFWD measurement, E_{lsf}, and plate loading test, E_{lpl}.

Figure 10 shows the relationship between initial deformation modulus, E_l, and cyclic deformation modulus, E_r, obtained in cyclic plate loading test and the SFWD measurement. Cyclic deformation modulus for comparison is the one at the cyclic load of 280kN/m^2, which is around the middle value of load range. In the same figure, the initial and cyclic deformation moduli obtained by SFWD measurement and by cyclic plate loading test have correlation coefficient from 0.93 to 0.95, which

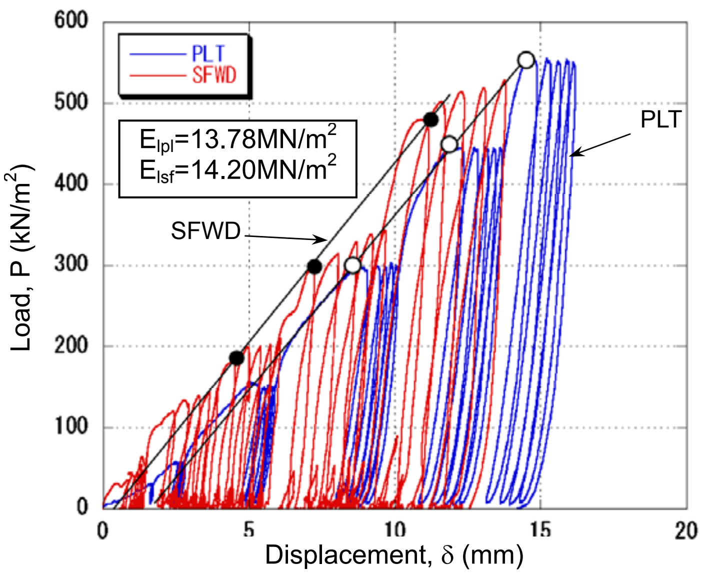


Figure 9 Comparison of Load Displacement obtained in SFWD Measurement and Plate Loading Test

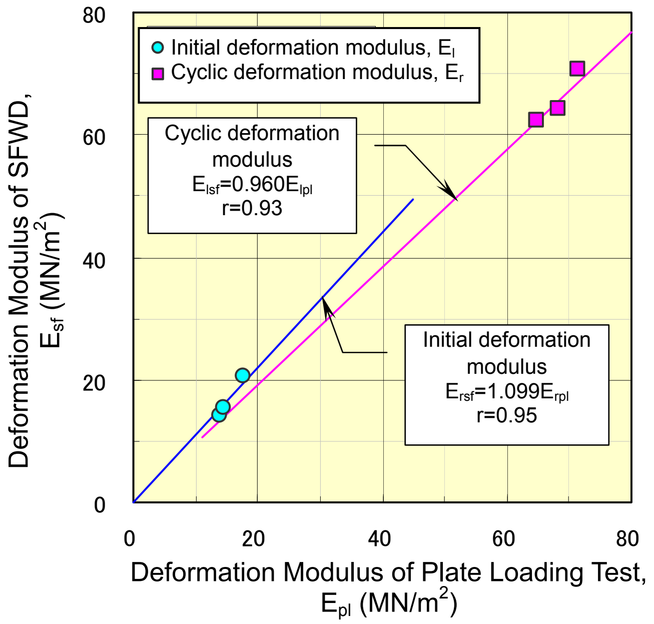


Figure 10 Relation between Deformation Modulus of Plate Loading Test and SFWD

means relatively high correlation.

Therefore, it can be concluded that it is highly reliable using SFWD in replace of plate loading test for quality control in compacting work of man-made ground like fill.

3.3 COMPARISON WITH IN-SITU CBR TEST

Figure 11 shows the results of SFWD and in-situ CBR test in case tested area contains crusher-run (1.5E_c). On this load-displacement relation line of in-situ CBR test, CBR deformation modulus, E_{cbr}, is defined as gradient of linear part at initial stage under monotonous load. In this case, in-situ CBR test and SFWD measurement yields almost the same deformation modulus.

Figure 12 shows the correlation between deformation modulus obtained by SFWD measurement and CBR. As can be seen in this figure, deformation modulus by SFWD measurement and CBR are in very good agreement.

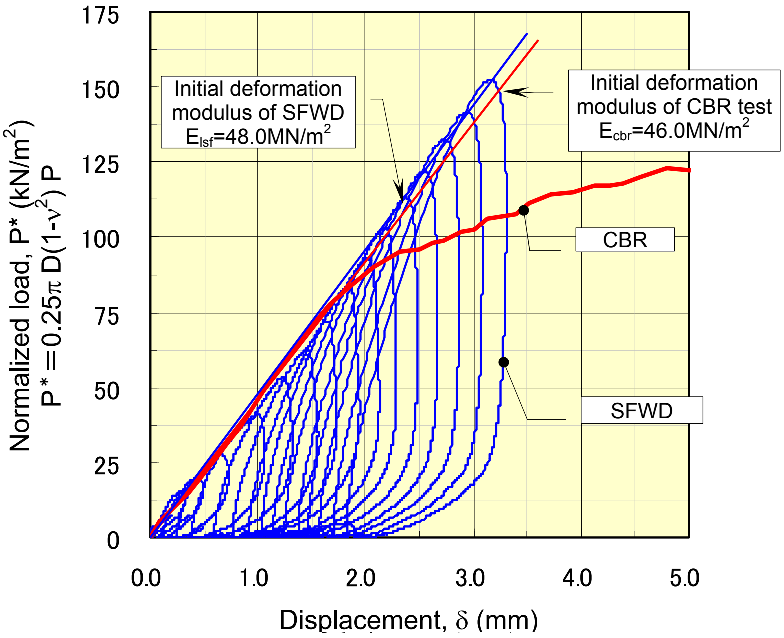


Figure 11 Relation between Normalized Load and Displacement of CBR and SFWD

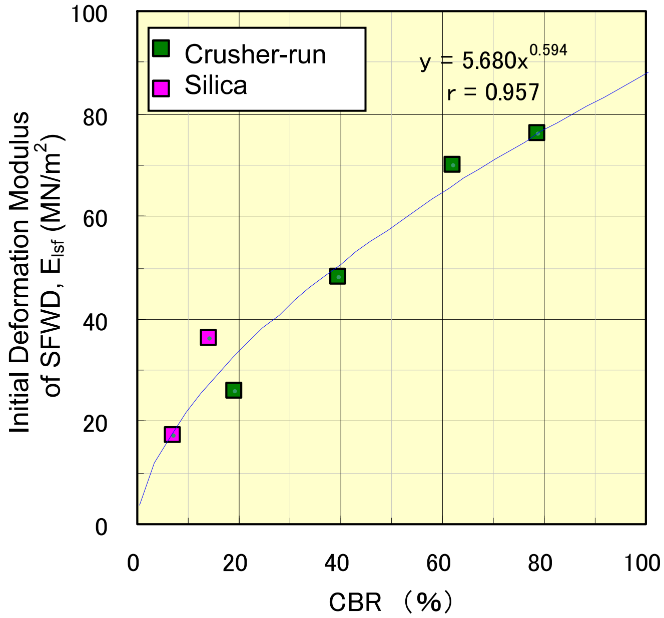


Figure 12 Relation between Initial Deformation Modulus of SFWD and CBR

Therefore, it can be concluded that it is possible to use SFWD in replace of in-situ CBR test for quality control in compacting work of man-made ground like road foundation.

4. EXAMPLE OF ACTUAL APPLICATION ON MAN-MADE GROUND

Actual applications on mudstone soil, cement-stabilized soil and sandy soil (decomposed granite soil) are selected as typical examples of in-situ measurement and stiffness evaluation using SFWD.

4.1 METHOD FOR EVALUATION OF GROUND STIFFNESS USING SFWD

For evaluating the ground stiffness using SFWD, the calibration measurement is the first necessary step in which SFWD measurement (ϕ450mm or ϕ300mm), Plate Loading Test (ϕ750mm or ϕ300mm), in-situ CBR test (ϕ50mm), density and water content measurement are carried out. Based

on the results obtained in these tests and measurements, correlation between entities like deformation modulus, bearing capacity coefficient, CBR, dry density, water content, etc can be figured out.

As shown in Figure 13, the measurement points are arranged in order to avoid the effect of load history caused by plate loading test, and the results of measurement are the average values of SFWD measurement at 4 positions, in-situ CBR test as well as measurement of density and water content at 2 positions.

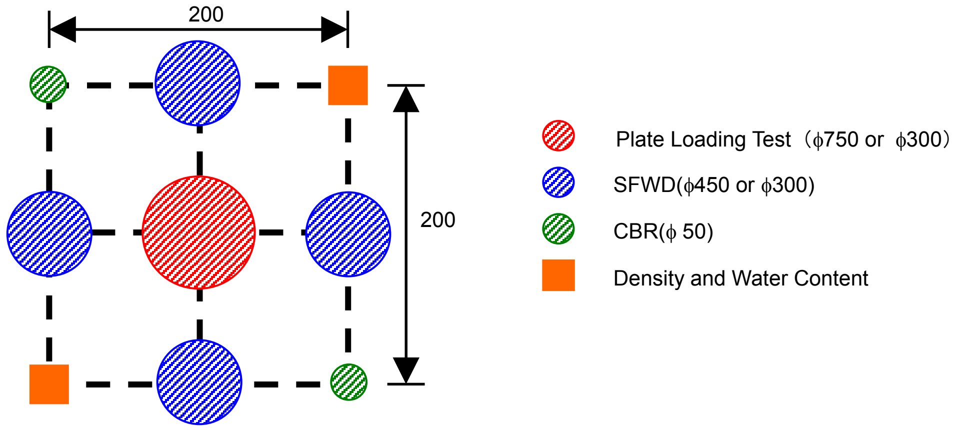


Figure 13　Outlines of Calibration Tests

4.2 STIFFNESS EVALUATION OF MUDSTONE GROUND, CEMENT STABILIZED GROUND

4.2.1 OUTLINES OF MAN-MADE GROUND

The measured ground was 4 types of man-made ground at an airport, including lower subgrade of fill, lower subgrade of cut, cement-stabilized and roller-compacted upper subgrade of fill (t = 300mm), upper subgrade of cut (t = 150mm).

Lower subgrade of fill is formed by mudstone soil (D_{max} = 150mm) and compacted with 20-ton vibrating roller (4 times). Average values of RI measurement after compacting work are dry density (ρ_d) of 1.897g/cm^3, water content(w) of 11.6%, and degree of compaction (D_c) of 98.7%

Lower subgrade of cut is made of new mudstone and leveled with bulldozer. Upper subgrade of fill and cut are cement-stabilized layers created by mixing with cement (50kg/m^3) and compacting by 20-ton vibrating roller (6 times)

4.2.2 MEASURED RESULTS AND DISCUSSION

Figure 14 shows the results of measurements at the same position using plate loading test and SFWD measurement. This figure shows that results of plate loading test and SFWD have similar cyclic history loops.

Figure 15 and 16 show the correlation between SFWD measurement and in-situ CBR test as well as plate loading test, respectively.

As shown in figure 15, a correlation of CBR values is relatively low. The result is believed due to the fact that the loading ϕ50mm rod used in-situ CBR test is quite sensitive to the fluctuation of ground condition. As shown in figure 16, a correlation between results of SFWD measurement and those of plate loading test is extremely high.

By using this correlation, it is possible to use SFWD instead of plate loading test for investigating the ground stiffness. It makes the work on quality control at site, especially for ground stiffness evaluation at large construction site, simpler and speedier.

4.3 STIFFNESS EVALUATION OF SANDY GROUND (DECOMPOSED GRANITE GROUND)

4.3.1 OUTLINES OF MAN-MADE GROUND

The tested ground was man-made ground including a fill made of decomposed granite soil and a cut made of decomposed granite soil.

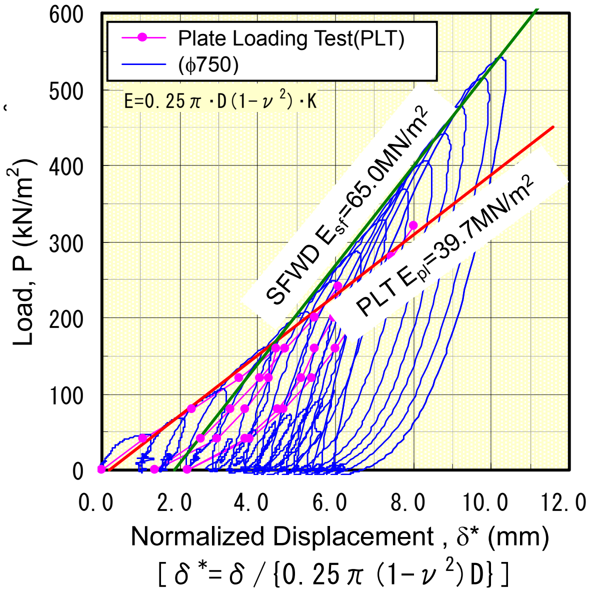


Figure 14 Relation between Load and Normalized Displacement

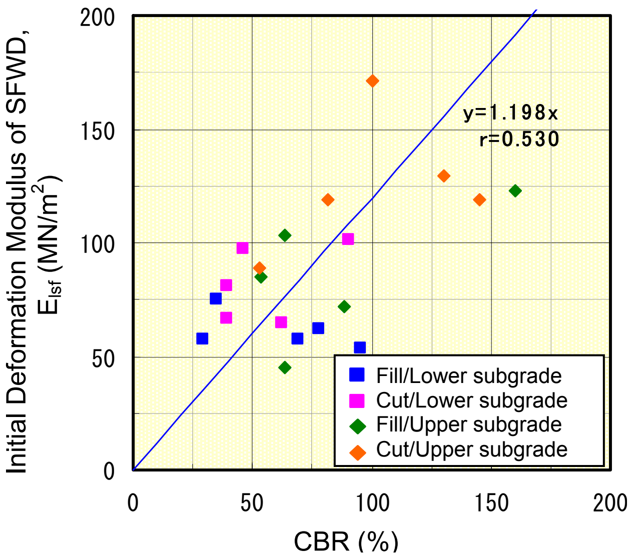


Figure 15 Relation between Initial Deformation Modulus of SFWD and CBR

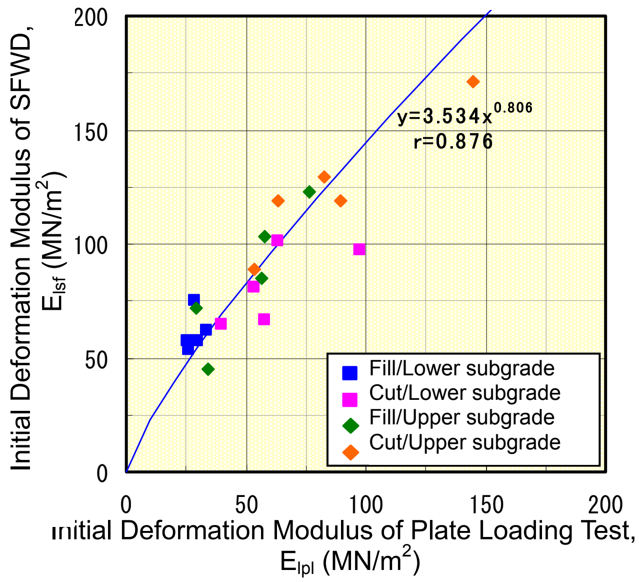


Figure 16 Relation between Initial Deformation Moduli of SFWD and that of Plate Loading Test

The decomposed granite soil for making fill has the maximum size of 19mm. Each 30cm layer is compacted by 10-ton roller in 8 times. After completing the required compaction, the sand replacement method is applied for confirming that the degree of compaction is at least 90%.

Cut is created by motor scraper.

4.3.2 MEASURED RESULTS AND DISCUSSION

Figure 17 shows the results of plate loading test and SFWD measurement on the same position. It can be seen that the plate loading test has similar record with SFWD measurement.

Figure 18 shows the correlation between SFWD result and that of plate loading test. It is clear that there is a good agreement between these methods. Therefore, the evaluation of bearing capacity coefficient and deformation modulus by using SFWD is as accurate as by using plate loading test.

SFWD was applied on the whole 5.6-hectre area of man-made ground for evaluating the deformation modulus. Figure 19 shows the contour of SFWD results that have been converted into initial

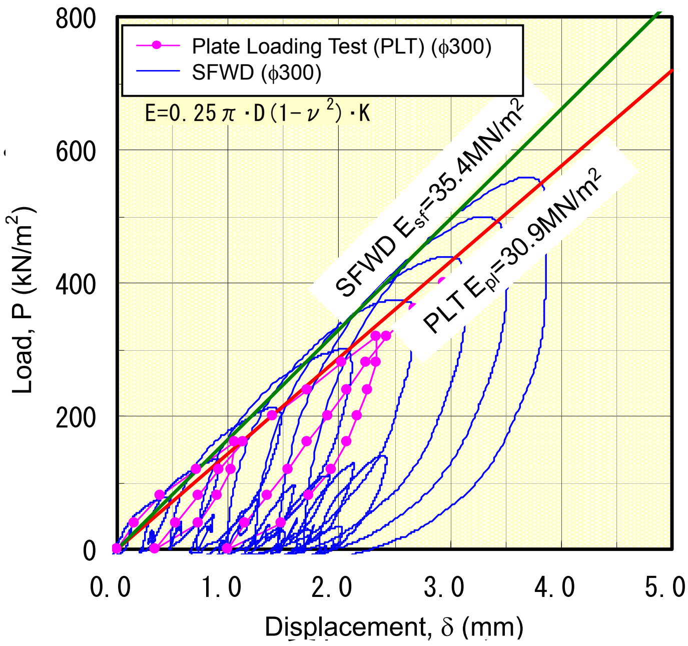


Figure 17 Relation between Load and Displacement

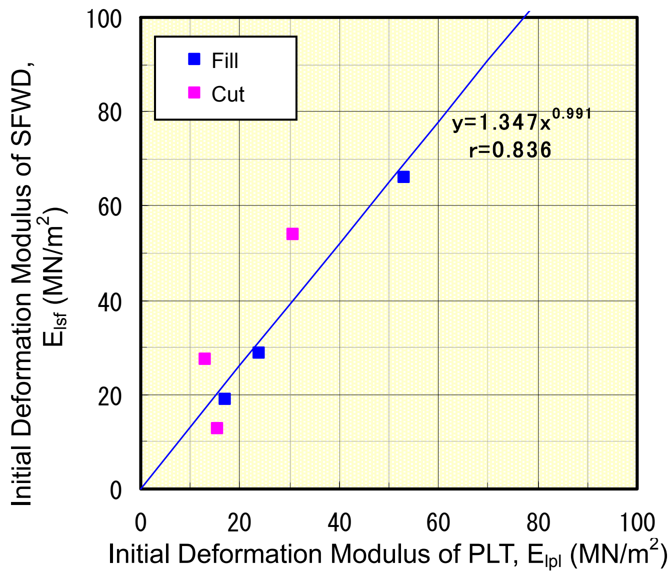


Figure 18 Relation between Initial Deformation Moduli of SFWD and Plate Loading Test (PLT)

deformation modulus as in plate loading test.

From this result, it can be concluded that SFWD is effectively applicable for large construction area and the evaluation of ground stiffness is undoubtedly very accurate.

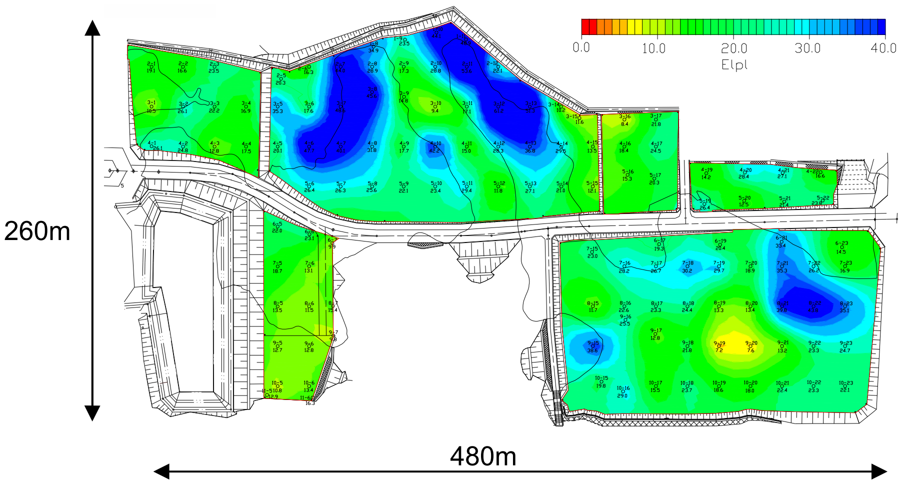


Figure 19 Contour of Initial Deformation Modulus obtained by SFWD

5. CONCLUSIONS

This paper reports the results of laboratory tests and the application of SFWD method on man-made ground. It was found that the measurement using SFWD method yields similar result of ground stiffness in comparison with plate loading test. In addition, for small-size gravel (D_{max}=40mm), SFWD measurement has a good correlation with in-situ CBR test.

By applying SFWD method, the measurement of ground stiffness has become simpler and speedier. Besides, it facilitates an effective confirmation of construction process, providing a timely feed back for evaluating the quality of ground making works on the real time basis.

The required time for each measurement using SFWD is approximately 10 minutes (actual time depends on the number of loading stages as well as the moving distance.). It is relatively short compared with plate loading test or in-situ CBR test which takes several hours. Therefore, it can be considered a great enhancement which changes the old idea that ground stiffness evaluation is always time-consuming and costly.

The final purpose is to ensure that a man-made ground satisfies the required performance by on-site quality control using this SFWD system. In addition, by digitalization and visualization of information, it is expected to be very useful for works related to management, maintenance and renovation after starting the utilization of the target ground.

It is also expected that SFWD method will be applied more and more in the coming time and has a great contribution on the development of road constructing technologies.

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